

Appendix E

Hydrologic Characterization Tests

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The characterization tests discussed in this section are designed primarily for determination of hydraulic/storage properties of selected basalt interflow and caprock horizons. Tables E.1 and E.2 list the various hydrologic test methods discussed in this section, the hydrologic parameter(s) estimates derived from their analysis, and the relative areal extent of their characterization (test scale). In addition to hydraulic/storage properties, field test programs would also include hydraulic head and hydrochemistry characterization of selected basalt interflow zones. These three characterization elements (i.e., hydraulic

Table E.1. Summary of Hydrologic Tests for Basalt Interflow Characterization

Test Method	Hydrologic Parameter ^(a)								Test Scale		
	K _h	K _{hd}	S	P _g	L	n _e	v _w	v _a	Local	Intermed.	Large
Dynamic Flowmeter	√	√							√	√	
Slug	√		√						√		
Slug Interference	√		√							√	
Constant-Rate Pumping/Injection – Single Well	√		√		√				√	√	
Constant-Rate Pumping/Injection – Multiwell	√		√		√					√	√
Tracer-Dilution		√				√	√		√		
Tracer-Pumpback						√		√	√		
Tracer-Forced Gradient						√				√	√
Gas Threshold				√							
Barometric Response Analysis			√		x				√	√	
(a) Nomenclature K _h = hydraulic conductivity in the horizontal direction; L/T K _{hd} = vertical distribution of K _h within test section; L/T n _e = effective porosity; dimensionless S = storativity; dimensionless P _g = entrance gas pressure required to displace water within interflow zone; F/L ² L = leakage response; (ability to detect) v _a = groundwater-flow velocity within aquifer; L/T v _w = groundwater-flow velocity within well; L/T Note: √ = only provides inferential/qualitative information x = method in development											

Table E.2. Summary of Hydrologic Tests for Basalt Interior/Caprock Characterization

Test Method	Hydrologic Parameter ^(a)						Test Scale		
	K _h	K _v	K _D	S	P _g	L	Local	Intermed.	Large
Pulse	√			√			√√		
Constant-Pressure Injection (Single Well)	√			√		√	√		
Constant-Pressure Injection (Multiwell)	√	√	√	√		√	√	√	
Ratio	√	√	√	√		√		√	√
Gas Threshold					√		√		
Laboratory Core Analyses		√			√		√√		
(a) Nomenclature K _h = hydraulic conductivity in the horizontal direction; L/T K _v = hydraulic conductivity in the vertical direction; L/T K _D = vertical anisotropy (K _v /K _h); dimensionless S = storativity; dimensionless P _g = entrance gas pressure required to displace water from/through caprock; F/L ² L = leakage response; (ability to detect) Note: √√ = very small scale √ = only provides inferential/qualitative information									

head, hydraulic/storage properties, and hydrochemical content) can be readily included in the test strategy adopted for borehole characterization. Several test strategies for borehole characterization are discussed below. In addition, a report on hydraulic property data from the CRBG at the Hanford Site by Strait and Mercer is included at the end of this appendix.

This appendix used the English system rather than the metric system of units because, by convention, drilling and testing activities in boreholes are based on English system units. Also, drilling equipment and supplies are dominated by the English system. Thus, by using the English system in this appendix, the hydraulic testing methods will be compatible with aquifer drilling and characterization activities.

E.1 Testing Strategies

The following discussion describes two test strategies that may be adopted at a reconnaissance borehole location that will be drilled to provide an initial assessment of the suitability of CRBG interflow zones for natural gas storage. After the initial single borehole characterization is completed, a decision can be made as to whether the more extensive characterization (e.g., tracer tests, gas injection/recovery test), using multiple-well test techniques is warranted (which would require drilling and characterizing additional, nearby boreholes).

The following testing strategy is limited to the discussion of test sequencing at an initial reconnaissance borehole within a study area. The objective of the two strategies is the same, i.e., to determine whether candidate basalt interflow zones are present for the effective storage and retrieval of natural gas,

and whether suitable caprocks are present to prevent significant leakage of the managed gas storage. In both test strategies, the collection of vertical/depth-dependent information pertaining to hydraulic properties, hydraulic head, and hydrochemical characteristics of the penetrated basalts are the primary investigative tools used to meet the test objectives. For discussion purposes, it is assumed that the well will be rotary drilled, of sufficient diameter to accommodate test equipment, and reflective of testing depths greater than 1,300 ft. It is also assumed that the testing to be discussed takes place solely within the Grande Ronde Basalt, and that overlying basalt and sedimentary units within the overlying Wanapum Basalt and Saddle Mountains Basalt (if present) have been effectively isolated using properly engineered cemented casing installations. Before isolation of the overlying Wanapum Basalt, it is also assumed that sufficient hydrologic characterization information (primarily hydraulic head and hydrochemistry) has been collected for selected lower Wanapum Basalt interflow zones for comparison with underlying Grande Ronde Basalt interflow test horizons. This information is valuable for assessing the Wanapum Basalt and Grande Ronde Basalt stratigraphic contact horizon (commonly delineated by the presence of the Vantage horizon, a sediment layer and/or an extensive saprolite layer) that has been noted previously as a regional confining layer separating groundwater flow systems within these two major CRBG formations.

Both test strategies include the collection of hydraulic head, hydraulic/storage properties, and hydrochemical characteristics of the penetrated basalt to meet the test objectives. How this is accomplished, however, is significantly different for the two test strategies. As might be expected, there are distinct advantages/disadvantages pertaining to characterization quality and costs that are associated with the strategy adopted, and variants or combinations of the two that could be used to meet specific test objective needs. This discussion, however, presents the two strategies—1) “drill first, test later,” and 2) “test as you go”—as separate entities.

Principal characteristics of the first strategy include conducting hydrologic test characterization elements only after the borehole has been drilled to its final completion depth within the Grande Ronde Basalt, geophysically logged for individual basalt flow characterization, and described geologically based on drill cuttings or core analysis.

The primary focus of the first strategy (testing strategy 1) is assessment of the hydraulic characteristics of intersected Grande Ronde Basalt interflow zones. The test program consists of two basic test elements: 1) composite testing of multiple interflow zones intersected within the borehole using dynamic flowmeter/pumping tests, and 2) detailed hydrologic characterization of selected interflow zone(s) using standard straddle packer tests. A brief description of the two test elements is provided in Section E.2. Briefly stated, however, productive, individual basalt interflow zones are identified from the dynamic flowmeter test results. The inflow production results, together with interflow thickness/storage capacity information obtained from geophysical log analysis, are used in selecting candidate interflow zones for detailed hydrologic test characterization. The principal objective of detailed hydrologic testing is to provide quantitative estimates of the hydraulic properties, static hydraulic head, and hydrochemical characteristics of the various interflows tested. When examined together, the hydraulic head and hydrochemical depth profiles provide valuable information pertaining to the interrelationships and isolation potential of groundwater contained within the respective basalt interflows.

The principal advantage of the first strategy (testing strategy 1) is the lower overall equipment costs (i.e., drilling rig time, downhole test system rental), when compared to other test strategies. A major disadvantage is that major pressure perturbations and groundwater incursions may be induced into the basalt formations surrounding the borehole during the extended, active borehole drilling phase. These drilling-induced effects may require lengthy extensions of test times to obtain representative static hydraulic heads and hydrochemical samples for the interflow zones selected for detailed testing.

The primary focus of the second strategy (testing strategy 2) is to provide detailed hydrologic characterization information at the time the interflow zone is penetrated. Drilling proceeds until the underlying dense basalt flow interior has been encountered. The newly drilled section of the borehole is then geophysically logged for basalt flow characterization. The interflow zone is tested exactly as in testing strategy 1, except that a single packer, test system is only required to achieve test zone isolation from the overlying open borehole section.

The principal advantages of testing strategy 2 are shorter test times and higher quality of the characterization data derived using this approach. Because the exposure time to drilling perturbations is minimized, test times required for acquiring representative static hydraulic heads and hydrochemical characteristics are greatly reduced. The major disadvantages of this strategy are the standby drilling rig and test equipment costs incurred when either activity is not taking place.

It should be noted that both strategies were used in DOE's basalt borehole characterization at the Hanford Site. As a generalization from the DOE experience, testing strategy 2 might be used where subsurface conditions within a region (i.e., from a geological or detailed hydrologic characterization perspective) are not well established. Conversely, testing strategy 1 might be used more efficaciously in more established areas, where nearby borehole data are available, and the need to develop a detailed vertical profile of hydraulic head and hydrochemistry between interflow zones is a lower priority.

Interflow zones selected for detailed testing are isolated within the open borehole using standard straddle packer test equipment systems. The hydrologic test system should also be equipped with a downhole shut-in tool (to expedite test zone recovery) and pressure sensors that allow monitoring of test interval response and borehole pressure response above and below the isolated interval. Monitoring borehole pressure responses above and below the interflow that is to be tested provides a means of assessing the integrity of packer seals during testing. Costly repeat tests can be minimized by careful selection of the packer depth settings within competent basalt flow interior sections above and below the test interflow zone. The final selection of competent packer depth settings can be greatly improved through use of borehole geophysical survey results (e.g., televIEWer, resistivity, sonic) and core log analysis.

A detailed interflow testing sequence is summarized below. Individual hydrologic test methods are discussed in more detail in Section E.2. A normal test sequence for interflow zone characterization might include the following elements:

- **Packer Inflation.** The test tool is positioned and packers are inflated to isolate the test interval.

- **Pressure Stabilization.** The downhole shut-in tool is closed and pressure is monitored to establish the static formation pressure. Time required for the pressure to approach static formation conditions depends on the severity of the borehole pressure drilling history effects and the hydraulic properties of the test interval.
- **Slug Testing.** This test is performed to provide initial estimates of test zone hydraulic properties (K and S), evaluate borehole damage/skin effects, and design the conduct of subsequent hydrologic test characterizations, e.g., constant-rate pumping test. This test is discussed in Section E.2.2.
- **Constant-Rate Pumping Test.** This test is conducted to provide detailed hydraulic property estimates, diagnostically evaluate operative aquifer conditions (e.g., leaky aquifer), and detect the presence of nearby hydrogeologic features (e.g., faults). Pumping tests also provide opportunities for the collection of representative water samples for detailed hydrochemical and isotopic analysis. This information is particularly useful for assessing the source and origin of groundwater and evaluating hydrologic intercommunication/ isolation between various interflow zones.
- **Recovery From Constant-Rate Pumping Test.** This test provides corroborative information (i.e., to drawdown pressure responses) during the constant-rate pumping test. The primary advantage for analysis of recovery data is its ease of application, and its insensitivity to flow rate variations that might have occurred during the constant-rate pumping test phase.

Following completion of detailed hydrologic testing of selected basalt interflow zones within the borehole, low-permeability caprock (flow interior) tests can be performed for zones immediately overlying the primary candidate interflow zone(s). The objective of these caprock tests is to provide initial, reconnaissance-level hydraulic properties for flow interior sections. Because of their inherently lower permeabilities, caprock tests generally take longer to complete (i.e., including pre-test pressure stabilization and testing) and are limited to smaller investigation areas around the borehole. These tests are discussed in Section E.3.

E.2 Field Tests – Interflow Zones

The following discussion pertains to hydraulic characterization tests that may be performed for characterizing basalt interflow zones, as part of implementing testing strategies (1) and/or (2). The hydrologic properties that can be determined and the relative measurement scale for the various tests are summarized in Table E.1.

E.2.1 Dynamic Flowmeter Surveys

Dynamic flowmeter/pumping tests provide a means of assessing, in a continuous fashion, the vertical distribution of hydraulic conductivity (K_{hd} ; see Table E.1) within an entire open borehole section. The K_{hd} distribution is determined directly by measuring the distribution of inflow rate into the borehole test section during a constant-rate pumping test. A variety of flowmeters are available for measurement of inflow rate, including mechanical (spinner), heat-pulse, electromagnetic, and acoustic flow meters. Generally, mechanical flow meters are reserved for pumping tests conducted in higher permeability

formations, while other flow-meter types are designed for lower inflow (or outflow) measurements. For most testing applications, commercially available mechanical flowmeters can be used successfully. Ideally, the flowmeter should be capable of resolving flow rates of at least $\pm 5\%$ of the composite discharge pumped from the entire borehole section (e.g., for a 100 gpm pumping rate, a minimum 5 gpm resolution is required).

The test is conducted by first installing the flowmeter (on wireline cable) at the bottom of the open borehole section to be characterized. A submersible pump with an adequate pumping capability (e.g., ≥ 100 gpm) for the given lift/depth conditions is then installed above the flowmeter in the upper cased well section. The pump depth setting within the borehole should be designed to allow sufficient draw-down capacity to perform a constant-rate pumping test in continuous fashion (e.g., 300 ft below the static water level). During pumping, the flowmeter is repeatedly raised and lowered at a specified constant-logging speed. The logging speed selected is based on the pumping rate and flowmeter/borehole characteristics. It is assumed that the logging rate will be within the range of 20 to 50 ft/min. A flowmeter/pumping test duration within the range of 2 to 8 h is expected to provide sufficient information for assessing the inflow characteristics of Grande Ronde interflow zones intersected by the borehole. Figure E.1 shows a schematic of test equipment and its deployment during performance of a dynamic flowmeter test. Conducting an ambient, “static” flowmeter profile of the open borehole section, before pump installation and performance of the “dynamic” flowmeter/pumping test also provides valuable information concerning “thieving” and producing zones under natural hydraulic gradient conditions.

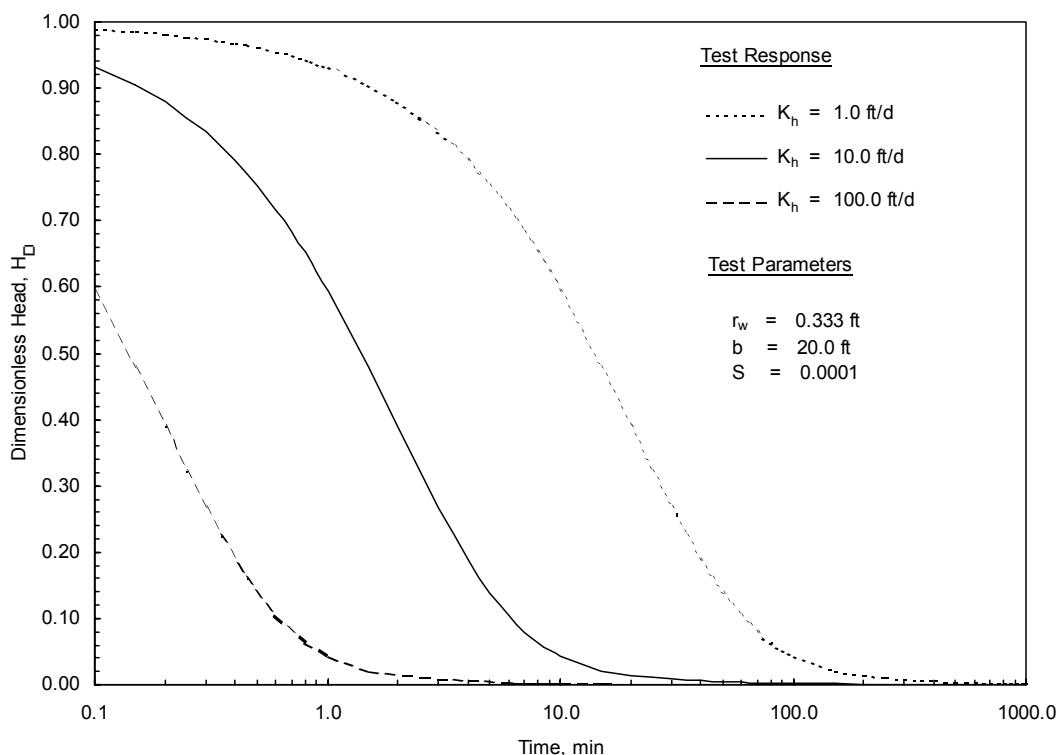


Figure E.1. Predicted Slug Test Response as a Function of Hydraulic Conductivity

The distribution of inflow to the borehole is determined by simple mass balance calculation methods. It is important that the borehole diameter over the open borehole section be known for quantitative analysis of the flowmeter data. This can be quantified by running a caliper log before conducting the flowmeter/pumping test element. Examples and descriptions of flowmeter/pumping test investigations are provided in Molz et al. (1989) and Rehfeldt (1989).

Analysis of flowmeter inflow data, using the Cooper and Jacob (1946) method, provides a means of calculating the hydraulic conductivity (K_h) for a particular interflow zone, once the inflow rate and composite borehole drawdown is known. The Cooper and Jacob (1946) method assumes that flow to the borehole is horizontal, and that horizontal head gradients are uniform away from the borehole. As indicated in Javandel and Witherspoon (1969) these conditions are established relatively early in composite borehole tests even for conditions where permeability contrasts between layers is large. Kabala (1994) provides a means for analyzing flow-meter tests for situations where the assumptions of Cooper and Jacob (1946) are not met.

Once pumping is terminated, sufficient time should be allotted (i.e., equivalent to the pumping time) to monitor recovery water levels back to pre-test, static conditions. The pressure responses measured during recovery can be analyzed to determine the composite transmissivity of all interflow zones intersected by the borehole. Examples of the methods and special procedures used for pumping test recovery analysis are presented in Earlougher (1977), Spane (1993), and Spane and Wurstner (1993).

E.2.2 Slug/Slug Interference

E.2.2.1 Slug Tests

Because of their ease of implementation and relatively short duration, slug tests are commonly used to provide initial estimates of hydraulic properties (e.g., range and spatial/vertical distribution of hydraulic conductivity, K). Because of the small displacement volumes employed, hydraulic properties determined using slug testing are representative of conditions relatively close to the borehole. For this reason, slug-test results are normally used in the design of subsequent hydrologic tests having greater areas of investigation (e.g., slug interference [Novakowski 1989; Spane 1996], and constant-rate pumping tests [Butler 1990; Spane 1993]).

To conduct this test, a known volume of water is instantaneously removed from (slug withdrawal) or added to (slug injection) the test interval. If a packer system is used, this can be performed by simply removing or adding water from the test tubing and opening the shut-in tool. The shut-in tool remains open during the recovery period. For open borehole test conditions, a large diameter rod of known volume can be *instantaneously* emplaced below or removed from the static water level within the well to initiate the test. Slug withdrawal tests can also be initiated using compressed air/gas to lower water level within the borehole. The use of compressed air to initiate slug withdrawal tests is discussed in Spane et al. (1996). The slug test response can be analyzed to estimate formation hydraulic properties (K_h and S ; see Table E.1). Figure E.2 provides examples of slug test recovery profiles as a function of hydraulic conductivity (K_h), for the listed well/aquifer conditions (well radius, $r_w = 0.333$ ft; interflow thickness,

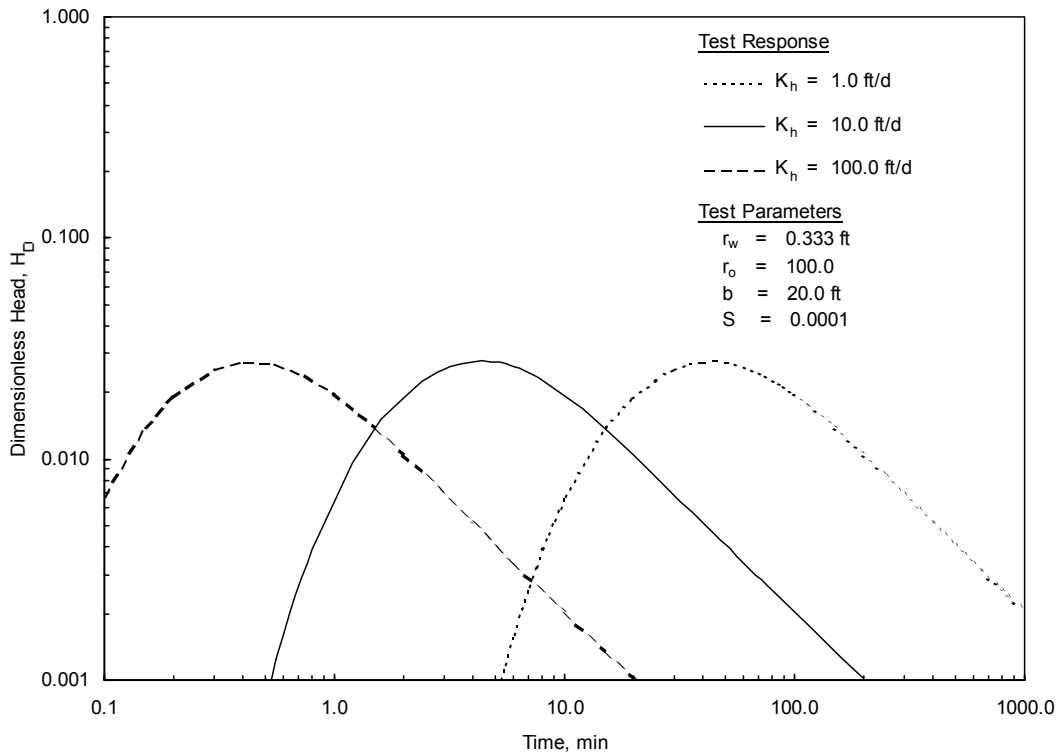


Figure E.2. Predicted Slug Interference Test Response as a Function of Hydraulic Conductivity

$b = 20$ ft; storativity, $S = 10^{-4}$). As shown in Figure E.2, the test response ($H_D = \text{observed response}/\text{initial stress applied}$; H_o/H) is a direct function of the interflow permeability, with faster test recovery associated with higher zone permeability. A detailed description of the design, performance and analysis of slug tests is presented in Butler et al. (1994) and Butler (1998).

E.2.2.2 Slug Interference Tests

For slug interference testing, an observation well is required to monitor the surrounding pressure wave induced by the slug test administered at a stress well. A particular advantage of multi-well slug interference testing (i.e., in comparison to single-well slug tests) is a higher degree of resolution for hydraulic property estimates (K_h and S ; see Table E.1), which are reflective of a much larger area of investigation. These features, together with the relative ease and short test durations required, make this test method particularly attractive for reservoir characterization applications.

Figure E.3 provides examples of slug interference test response at a distance of 100 ft from the stress well (slug well) for the same test conditions used in Figure E.2. The test response ($H_D = \text{observed response}/\text{initial stress applied}$; H_o/H) is a direct function of the interflow permeability; with faster test recovery associated with higher zone permeability. For the example shown in Figure E.3, an initial 100-ft “slug” stress applied at the stress well would produce a peak pressure perturbation of ~ 3 ft at the point of observation, with the inter-well permeability controlling the arrival time of the slug interference response.

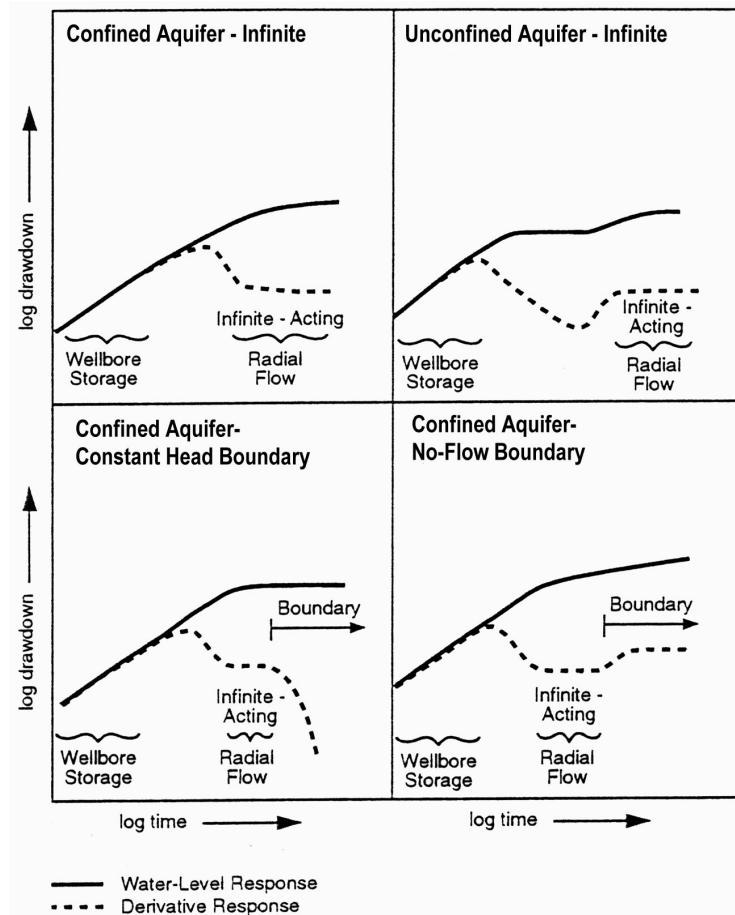


Figure E.3. Characteristic Log-Log Drawdown and Drawdown Derivative Plots for Various Hydrogeologic Formation and Boundary Conditions (adapted from Spane and Wurstner 1993)

Detailed descriptions of the design, performance and analysis of slug interference testing is provided in Novakowski (1989), Spane (1992), Spane (1996), and Spane et al. (1996).

E.2.3 Constant-Rate Pumping

During constant-rate pumping tests, groundwater is withdrawn from a well, which is discharge-regulated and maintained at a uniform rate. The water-level (pressure) response within the well is monitored during the active pumping phase and during the subsequent recovery phase following termination of pumping. The analysis of the drawdown and recovery water-level response within the pumping well (and for multi-well tests any nearby observation wells) provides a means for estimating hydraulic properties (see Table E.1) of the interflow zone(s) tested, as well as for discerning formational and non-formational flow conditions (e.g., wellbore storage, skin effects, presence of boundaries and leakage). It should be noted that constant-rate injection tests apply equally to the discussion in this section pertaining to pumping tests. In some situations where disposal of pumped groundwater may be

an issue (and a large, dependable water source is available for injection), constant-rate injection tests may be preferable. Standard analytical methods used for the analysis of constant-rate tests include type-curve matching and straight-line methods.

Type-curve-matching methods are best applied to observation well data and not to pumping wells because of the additional head losses that occur at the pumped well. They can be used for pumped well analyses, however, if certain assumptions pertaining to well efficiency (i.e., well-skin effects = 0) or the test interval (e.g., S is known) are made. This is the approach taken for single-well pumping test analysis within the petroleum industry. Type-curve-matching methods commonly used in the analysis of pumping test responses include those described in Theis (1935), Hantush (1964), and Neuman (1975).

For straight-line analysis methods, the rate of change of water levels within the well during draw-down and/or recovery is analyzed to estimate hydraulic properties. Because well effects are constant with time during constant-rate tests, straight-line methods can be used to analyze quantitatively the water-level response at both pumping and observation wells. The semilog, straight-line analysis techniques commonly used are based on either the Cooper and Jacob (1946) method (for drawdown analysis) or the Theis (1935) recovery method (for recovery analysis). These methods are theoretically restricted to the analysis of test responses from wells that fully penetrate nonleaky, homogeneous, isotropic, confined aquifers. Straight-line methods, however, may be applied under nonideal well and aquifer conditions if infinite-acting, radial flow conditions exist. Infinite-acting, radial flow conditions are indicated during testing when the change in pressure, at the point of observation, increases proportionately to the logarithm of time.

Log-log plots of water level versus time have traditionally been used for diagnostic purposes to examine pumping test drawdown data. More recently, the derivative of the water level or pressure has also been used as a diagnostic tool. Use of derivatives has been shown to improve significantly the diagnostic and quantitative analysis of various hydrologic test methods (Bourdet et al. 1989; Spane 1993; Spane and Wurstner 1993). The improvement in test analysis is attributed to the sensitivity of pressure derivatives to various test/formation conditions. Specific applications for which derivatives are particularly useful include the following:

- determining formation-response characteristics (nonleaky or leaky; confined or unconfined aquifer) and boundary conditions (impermeable or constant head)
- assisting in the selection of the appropriate type-curve solution through combined type-curve/derivative plot matching
- determining when infinite-acting, radial flow conditions are established and, therefore, when straight-line analysis methods are applicable.

Figure E.3 shows selected examples of log-log drawdown and derivative responses that are characteristic of some commonly encountered formation conditions. Spane (1993) provides a summary discussion on the use of standard and derivative-based analytical methods for constant-rate tests.

E.2.4 Tracer Tests

A variety of single- and multi-well tracer tests are available that can be used for interflow zone characterization. Three tracer tests that may be particularly relevant for basalt interflow characterization include tracer-dilution, tracer drift/pumpback, and multi-well, forced-gradient tests. Table E.1 summarizes the various hydrologic parameters and areas of investigation for individual tracer test techniques.

For the tracer-dilution test, a solution with known tracer concentration is placed within the isolated test interval section. A particularly useful tracer for groundwater studies from a standpoint of non-reactivity, availability, and in-situ detection is bromide ion (Br^-). Initial bromide tracer concentrations normally used within the borehole are within the range of 100 to 200 mg/L (Br^-). The decline of tracer concentration (i.e., “dilution”) with time within the test interval can be monitored directly using a downhole bromide probe. (Note: If vertical distribution of permeability within the test interval is desired, then a vertical array of bromide specific-ion electrode probes can be installed at known depth intervals.) Based on the dilution characteristics observed, the in-well flow velocity (v_w) and/or average hydraulic conductivity may be estimated for the specific interflow zone tested. This particular tracer method is invalid if in-well vertical flow conditions exist. This is why tracer-dilution tests are not usually applicable for testing large test intervals or open borehole sections. It should be well suited, however, for characterizations of typical interflow zone thickness of ≤ 30 ft. The presence of vertical flow within the well screen can also be identified by comparison of individual probe dilution response patterns, as described in Spane et al. (2001a, b). Descriptions of the performance and analysis of tracer-dilution test investigations are provided in Halevy et al. (1966), Hall et al. (1991), and Hall (1993).

For the tracer drift and pumpback test, a non-reactive (conservative) tracer of known concentration and volume is injected into the surrounding basalt interflow zone and allowed to “drift” away from the well for a specified residence period (e.g., 1 to 10 days). After the specified time is attained (usually determined by monitoring the dilution of the in-well concentration), a pumpback/constant-rate pumping test is initiated. The objective of the tracer pumpback is to “recapture” the tracer that has moved from the well to the surrounding aquifer. Tracer recovery is best determined by measuring the tracer concentration in water pumped from the well using an in-line, specific-ion/tracer probe within the pumped discharge water. Discrete groundwater samples are normally collected for laboratory analysis during the pumpback phase for corroboration of the in-line results. This tracer test can be combined with other characterization methods (e.g., tracer-dilution, constant-rate pumping) for field test efficiency. Characterization information obtained from the drift/pumpback test includes effective porosity (n_e) and groundwater flow velocity (v_a). Like tracer-dilution testing, this tracer method is particularly sensitive to well effects and their impact on the surrounding flow field (Drost et al. 1968; Kearn et al. 1988). It is unknown if these sensitivities are relevant for basalt interflow zone characterization. Detailed descriptions of the performance and analysis of single-well, tracer injection/withdrawal tests are included in Güven et al. (1985), Leap and Kaplan (1988), and Hall et al. (1991).

For multi-well, forced-gradient tracer tests, a steady-state hydraulic gradient is established between a dual-well couplet. Once established, a conservative tracer (e.g., bromide) is administered at a neighboring monitor well, and the tracer breakthrough is monitored at the pumping (extraction) well location.

The analysis of the tracer breakthrough pattern (i.e., time-concentration profile) provides intermediate-scale information concerning aquifer dispersivity and effective porosity. The time required for establishment of steady-state conditions and tracer breakthrough is dependent on the existing aquifer hydraulic properties, injection/withdrawal rates, and well spacing (distance). Based on the expected test site conditions, tracer breakthrough may be anticipated within a range of 1 to 7 days. Multi-well forced-gradient tests can be conducted in several configurations: one where both wells are active and recirculation is used (i.e., an injection and extraction well couplet), and with only one active well (i.e., extraction well). Each configuration has advantages for various well/test site conditions. Detailed descriptions of the general performance and analysis of multi-well, forced-gradient tracer tests are provided in Gelhar (1982), Molz et al. (1986, 1988), and Huyakorn et al. (1986). An example of a multi-well, forced-gradient tracer test conducted for an interflow zone within the Grande Ronde Basalt is reported in Leonhart et al. (1982, 1985).

E.2.5 Gas-Threshold Pressure Test

The creation of a natural gas storage reservoir within basalt interflow zones will impose multiphase condition (i.e., gas and water) within the subsurface. For candidate interflow zones and overlying low-permeability caprocks, capillary forces may hold groundwater within the pore interstices, even in the presence of a pressure gradient. The pressure required to overcome the capillary forces within an interflow zone to displace the “held” water with injected gas is referred to as the gas entry or gas threshold pressure (GTP). Because of the greater permeability and porosity afforded by interflow zones, GTP would be expected to be considerably lower than that for low-permeability/porosity flow interior caprock layers. Determination of the GTP within caprocks, however, is particularly important from a standpoint of leakage, since gas injection pressures within the candidate reservoir zone (interflow zone) are maintained at a pressure below the GTP within the caprock, and the effects of capillarity will impede the vertical leakage of stored reservoir gas. The importance of determining the GTP and capillary pressures within a reservoir horizon at the onset, as well during, the management of natural gas reservoirs within an aquifer system is discussed in Schafer et al. (1993).

For sedimentary formation caprocks, the GTP information is commonly determined by laboratory core tests, which (because of the small-scale dependence) require a large number of core test results for effective statistical analysis. Because permeabilities of basalt interflow and flow interior/caprock layers are inherently dependent on irregular fracture connectivity, the applicability of core analysis results for these units is highly questionable and best addressed using field tests. To conduct a field gas threshold pressure test (GTPT), gas must be emplaced within the entire testing string, and the test interval cannot be exposed to significant under- or over-pressurization before initiation of the test. To conduct a GTPT, the following pretest procedures are proposed:

- Use a straddle packer test system to isolate a candidate interflow zone or caprock interval within the borehole (see Figure E.4).
- Replace the water in the borehole test section (as completely as possible) by injecting gas into the isolated borehole test section using a separate gas injection line that extends from the surface through the upper packer and into the borehole test interval.

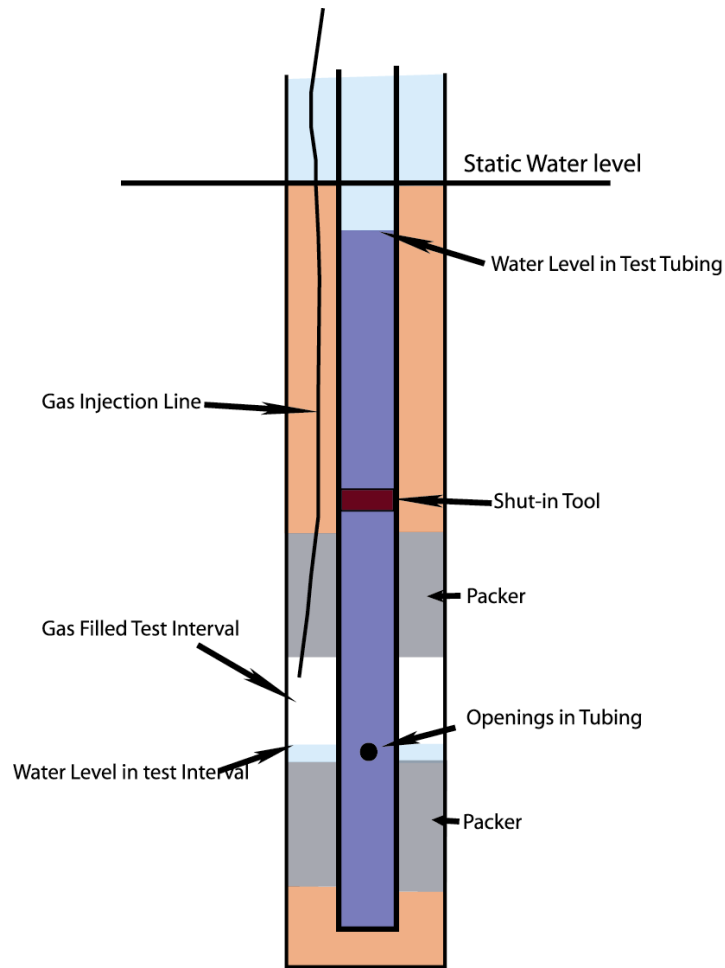


Figure E.4. Straddle Packer Test System

- To displace water from the borehole test section, gas is injected (while the shut-in tool is open) and with the water level in the test tubing string at a level slightly lower than prevailing static formation head conditions. To keep gas from being forced prematurely into the formation during water displacement, gas pressure should not exceed static formation pressure conditions.
- The displaced water from the borehole test section flows through the openings in the test tubing, which are located immediately above the bottom packer. The displaced water exits through the shut-in tool and into the overlying test tubing string.
- When all the water has been displaced from the test section, (as determined from measurement of the injected gas volume), the shut-in tool is closed and gas pressure maintained at approximately static hydraulic head conditions until the start of the GTPT test.

After the water in the test interval has been replaced by gas, the GTPT is initiated by gradually increasing the gas pressure and observing the point where continuous injection of gas into the formation

begins. It is preferable to introduce the gas into the test interval using a small diameter gas injection line, rather than the test tubing string to reduce the volume of gas required to fill the test system and the possibility of test system leakage that can occur at tubing string joint connections. An extended gas threshold pressure test (EGTPT) can also be conducted by allowing the gas injection to continue at constant pressure and observing changes in flow rate over time. Analysis of the changes of flow rate with time can be used to provide additional information pertaining to test formation hydraulic properties, using the analysis approaches described in this section.

E.2.6 Barometric Response Analysis

Barometric fluctuations represent an areal, blanket stress applied directly at land surface and to the open well water-level surface. The manner in which a well/aquifer system responds to changes in atmospheric pressure is variable and directly related to the degree of aquifer confinement and the hydraulic/storage characteristics of the well/aquifer system. Rasmussen and Crawford (1997) and Spane (1999, 2002) describe three conceptual models of water-level measurements in wells to barometric pressure change. These models include an instantaneous well response within confined aquifers, a delayed well response within unconfined aquifers (because of the delayed transmission of barometric pressure through the vadose zone), and a delayed well response associated with well characteristics (i.e., wellbore storage and well-skin effects).

Plots for the three well-response models are shown in Figure E.5. The plots show the time-lag dependence of each barometric response model associated with a unit step change in atmospheric

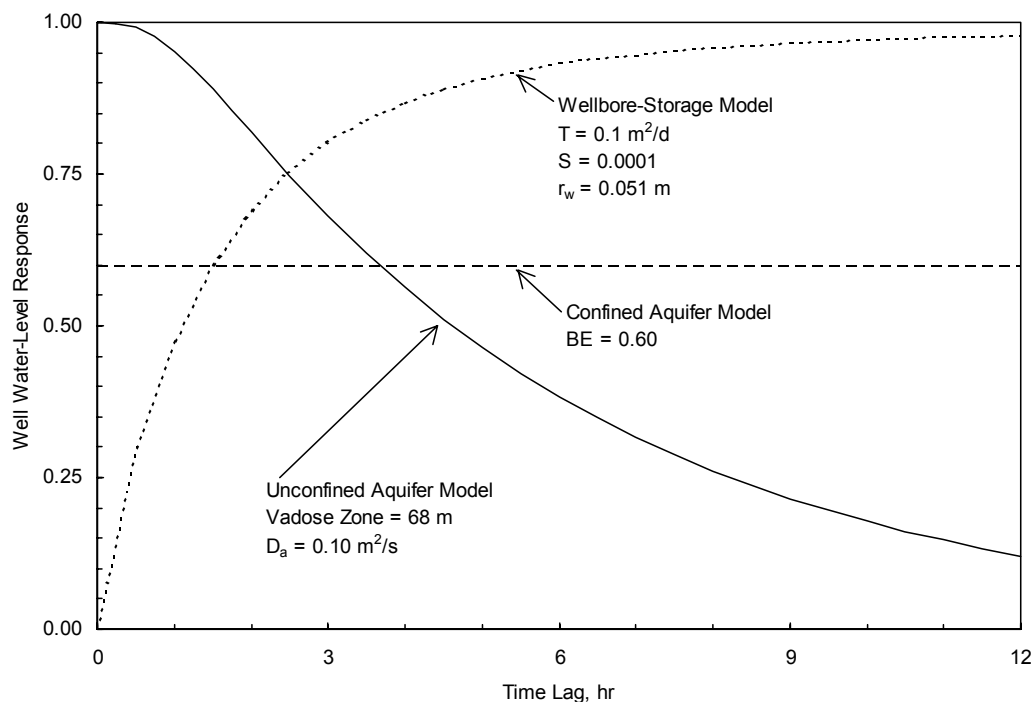


Figure E.5. Diagnostic Well/Barometric Response Models (adapted from Spane 1999)

pressure. The plots were developed by performing multiple-regression analysis of well response to barometric pressure change over a time-lag period, as indicated in Rasmussen and Crawford (1997) and Spane (1999). As shown in the figure, each barometric response model has a distinguishing pattern that can be used diagnostically for response-model identification.

Of relevance in assessing the suitability of basalt interflow zones for natural gas storage is whether they exhibit leaky or nonleaky characteristics. As shown in Figure E.5, for completely nonleaky behavior, a confined aquifer exhibits no time-lag dependence, and a uniform well response (i.e., barometric efficiency, B_e) is indicated. Although not yet fully developed, leaky confined aquifer models are expected to exhibit a diagnostic pattern, which readily distinguishes them from nonleaky behavior. Additional research is required, however, to develop this diagnostic approach. The ability to distinguish leaky versus nonleaky behavior with simple barometric monitoring tests represents significant characterization cost savings over more expensive standard hydrologic tests. For barometric response characterization, the collection of hourly barometric and well pressure data is only required for minimum time periods of 1 to 2 weeks. (Note: Longer time periods up to 4 weeks may provide optimum diagnostic characterization.) Additionally, with the installation of a multi-level monitory borehole system, barometric response information from all candidate basalt interflow zones within a borehole can be collected during one data collection period.

An additional application of barometric response analysis is that the effective porosity, n_e , of interflow zones can be *indirectly* assessed using the interflow storativity (S), which is determined by multi-well, interference tests (e.g., constant-rate pumping) together with the observed (B_e), in Jacob's classic barometric efficiency relationship (Jacob 1940):

$$S = (\phi \gamma_w b) / (E_w B_e) \quad (E.1)$$

where ϕ = effective porosity; dimensionless

γ_w = specific weight of the interflow groundwater; F/L^3

b = interflow zone effective thickness; L

E_w = bulk modulus of the interflow groundwater; F/L^2

B_e = barometric efficiency; dimensionless

E.3 Field Tests - Caprock Zones

Hydraulic tests conducted in low-permeability formations can be significantly affected by borehole pressure history, temperature changes of fluid in the borehole, volume changes caused by deformation of test equipment, and the presence of gas in the formation and test system (Pickens et al. 1987). Care, therefore, should be taken to minimize these extraneous effects and to account for them in the test analysis. A normal test sequence for a low-permeability caprock interval would include the following steps:

1. **Packer Inflation.** The test tool is positioned, and packers are inflated to isolate the test interval.
2. **Temperature Stabilization.** The shut-in tool is open, and water level in the test tubing is approximately equal to the estimated static hydraulic head for the test formation. If the shut-in tool is closed

immediately after setting the test equipment, temperature changes of the fluid within the low-permeability interval may cause pressure changes. This period also allows effects from deformation of the test equipment to dissipate.

3. **Pressure Stabilization.** The shut-in tool is closed, and pressure is monitored to establish a pressure trend that can be extrapolated for the remaining test period. The pressure may stabilize and approach static formation conditions depending on the severity of the borehole pressure history effects and the hydraulic properties of the test interval.
4. **Pulse Withdrawal Test.** By removing water from the test tubing above the closed shut-in tool and then quickly opening and closing the shut-in tool, the interval is subjected to an under-pressure pulse. A small volume of water is removed from the interval in this process, and this volume will be determined from measurements of the water level in the test tubing before and after pulse test initiation. Recovery from the pressure pulse can be analyzed to estimate the hydraulic conductivity and storativity of the test interval (see Section E.3.2). However, because of the small volume of water removed from the test interval, these results pertain only to the formation very near to the borehole wall.
5. **Constant-Head Injection Test.** For this test, the shut-in tool is opened and water injected into the test interval under constant head (pressure). For cases where artesian flowing conditions exist or formation pressure conditions are too high, a constant-head withdrawal test can be performed by removing water at a sufficient rate to maintain a constant water level in the test tubing. The measured injection or withdrawal rate during the test can be analyzed for determining hydraulic properties for the test interval, as discussed in Section E.3.3.
6. **Recovery From the Constant-Head Test.** Following completion of the constant head test, the shut-in tool is closed, and pressure within the test interval can be monitored. If a sufficient amount of data is collected following termination of the injection or withdrawal test, these data can be analyzed to corroborate the hydraulic properties determined from earlier tests.

Caprock leakage and/or vertical permeability are the important properties for assessing the viability of a natural gas storage reservoir within basalt interflow zones. Flow interior/caprock leakage/ vertical permeability can be determined by a number of direct and indirect test methods. Direct tests are conducted directly within the caprock or caprock samples for the determination of vertical permeability, and include laboratory core analysis, single- and multi-well pulse tests (pressurized slug tests), and constant-pressure injection tests. Indirect test methods are conducted within the candidate basalt interflow horizon, with vertical permeability or leakage in the overlying basalt caprock/flow interior determined by either the:

- departure from the theoretical nonleaky response for the test interflow zone
- presence of an observable hydrologic response within the overlying basalt interflow zone (i.e., above the caprock)
- ratio of the caprock to test interflow zone response.

The following discussion pertains to hydraulic characterization tests that may be performed for characterizing basalt flow interior/caprock zones. The hydrologic properties that can be determined and the relative measurement scale for the various tests are summarized in Table E.2.

E.3.1 Laboratory Core Analysis

Because of their inherent small size, core samples provide characterization results reflective of very small-scale conditions, which are not readily transferable for determining large-scale caprock leakage conditions. In addition, groundwater flow within a basalt caprock/flow interior is controlled entirely by the occurrence of open/connected fracture zones. Core samples that do not contain fractures provide information pertaining only to basalt matrix permeability. Cores with fractures may not be representative of the flow interiors as a whole, due to the uncertainty of whether the fractures are natural or induced by the coring process, and whether the core fracture(s) actually represent connected in-situ fracture system conditions. For these reasons, small-scale core samples are not recommended for the primary determination of basalt caprock vertical permeability.

E.3.2 Pulse

Discussions pertaining to pulse and constant-pressure injection testing within basalt flow interiors are provided in Spane and Thorne (1985) and Thorne and Spane (1985). Both methods provide an average bulk permeability of the caprock interval tested and have limited areas of investigation. For the case of pulse testing, hydraulic caprock information derived from the test is representative of conditions in proximity of the borehole (e.g., several borehole diameters). Although results from pulse and constant-pressure injection tests are not directly applicable for assessing caprock leakage, valuable vertical permeability information can be derived when these tests are designed to test the entire caprock thickness, and the permeability results are compared with other flow interior tests conducted at surrounding borehole sites.

Pulse or pressurized slug tests have been widely used for hydraulic characterization of low-permeability (i.e., $\leq 10^{-9}$ ft/s) test formations. They differ from standard slug tests in that the dissipation of the instantaneous stress occurs under closed system conditions. As shown by Bredehoeft and Papadopoulos (1980), the closed system conditions cause the stress to dissipate more rapidly than a standard slug test response, since the pressure change during a pulse test is controlled by fluid volume changes associated with the compressibility/elasticity of water and the surrounding test system. To illustrate this dramatic difference in test rate dissipation, Figure E.6 compares the response differences for a slug and pulse (closed-system slug) test conducted for the specified low-permeability test conditions specified in the figure. The more rapid decline exhibited for the pulse test response (~ 1000 min), as compared to the slug test ($> 1.0 \times 10^6$ min), demonstrates why pulse testing is more viable for caprock characterization.

The analytical equations used for analysis of slug tests (e.g., Cooper et al. 1967) can also be used to analyze pulse tests (Bredehoeft and Papadopoulos 1980). The equations, however, must be modified to account for the closed-system test conditions, by replacing the term for well casing radius, r_c , with:

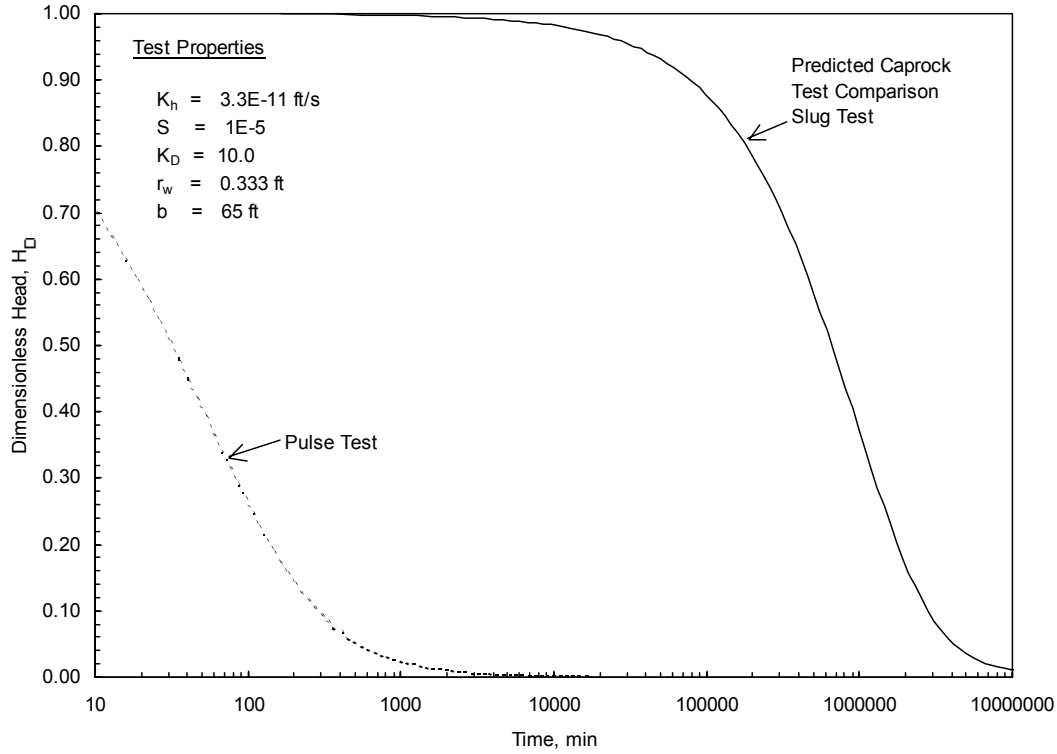


Figure E.6. Comparison for Pulse and Slug Test Responses

$$r_c = (V_w C_w \gamma_w / \pi)^{1/2} \quad (\text{E.2})$$

where V_w = closed test system volume; $[L^3]$
 C_w = compressibility of water; $[L/F]$
 γ_w = specific weight of water; $[F/L^3]$.

Neuzil (1982) also identified the importance of evaluating the compressibility of the test system, C_{obs} , and replacing the C_w with this parameter, when $C_{obs} > C_w$ for the relationship expressed in Equation (E.2).

Because the volumes of fluid are smaller (per unit pressure change) during pulse tests in comparison to slug tests, the radius of investigation is accordingly smaller. This fact makes pulse tests more susceptible to near well formation heterogeneities and skin effects. These characteristics and susceptibilities of pulse tests were described in detail in Moench and Hsieh (1986). Summaries of the application and interpretation of pulse tests for low-permeability characterization are provided in Thorne and Spane (1985) and Spane and Thorne (1985).

E.3.3 Constant-Pressure Injection

For constant-pressure (head) injection tests, a constant overpressure is applied that is greater than static test interval pressure. The injection rate declines during the test as a function of time, eventually reaching a steady-state flow rate. The early-time decline in injection rates can be analyzed using the

transient straight-line solution presented by Jacob and Lohman (1952). Late-time, steady-state injection rates can be analyzed using the equation relationship presented in Zeigler (1976).

For detailed characterization of low permeability caprocks, it is recommended that multi-level constant-pressure injection tests be conducted. In a multi-level test, injection pressures are systematically increased with time, and the associated steady-state injection rates are recorded for each injection pressure. The advantage of conducting a multi-level injection test over a single-injection pressure test is the ability to assess dependence of permeability to injection pressure level. Permeability-pressure dependence may occur in fractured rock types (e.g., flow interiors) and clays. If no dependence is evident, a straight-line relationship between steady-state injection rate and injection pressure will be indicated. Examples of multi-level injection pressure tests and their analysis are provided in Spane and Thorne (1985).

Analysis of recovery pressures following termination of constant injection tests in low-permeability intervals usually is not performed. This is due to the excessive time required to reach radial flow conditions. For intermediate and/or higher permeability caprock intervals, however, recovery analyses can be used. Constant-rate recovery methods cannot be used unless steady-state injection rates are maintained for prolonged periods. In these instances, multi-rate analytical methods (to take into account the non-uniformity in injection rates) must be used. A description of the various multi-rate analytical approaches is presented in Earlougher (1977).

The radius of investigation for constant-pressure injection tests is greater than that for pulse tests, but still generally <8 ft for tests of 5 h or less, conducted within basalt flow interiors with hydraulic conductivities of $\leq 10^{-11}$ ft/s. Figure E.7 shows the difference depths of investigation surrounding the borehole for the listed caprock and test conditions.

E.3.4 Indirect Interflow Leakage Response Tests

Caprock leakage can be inferred indirectly from hydraulic tests conducted within candidate basalt interflow zones. Basically, these methods rely on departures from theoretical nonleaky interflow responses, as the basis for assessing caprock leakage. There are several significant drawbacks associated with indirect methods. Commonly, they are insensitive to all but significant leakage, and, if detected, they do not discriminate whether leakage is occurring in overlying or underlying confining caprock horizons.

To demonstrate the insensitivity of leakage on interflow response, Figure E.8 shows the predicted drawdown and drawdown derivative response for a constant-rate pumping test conducted within a basalt interflow zone for selected leaky caprock conditions. For comparison, the ideal interflow response for nonleaky (impermeable) caprock conditions is also included. The predicted responses were calculated based on a pumping rate of 150 gpm, and the following candidate interflow properties: hydraulic conductivity (K) = 3.3×10^{-5} ft/s (~ 1 darcy); interflow storativity (S) and caprock storativity (S') = 1×10^{-4} ; interflow thickness (b) and caprock thickness (b') = 100 ft; and observation borehole distance (r_o) = 300 ft. As shown, the drawdown derivative plot can be used to determine definitively the presence of leakage within the interflow test response; however, for the test conditions considered, a threshold

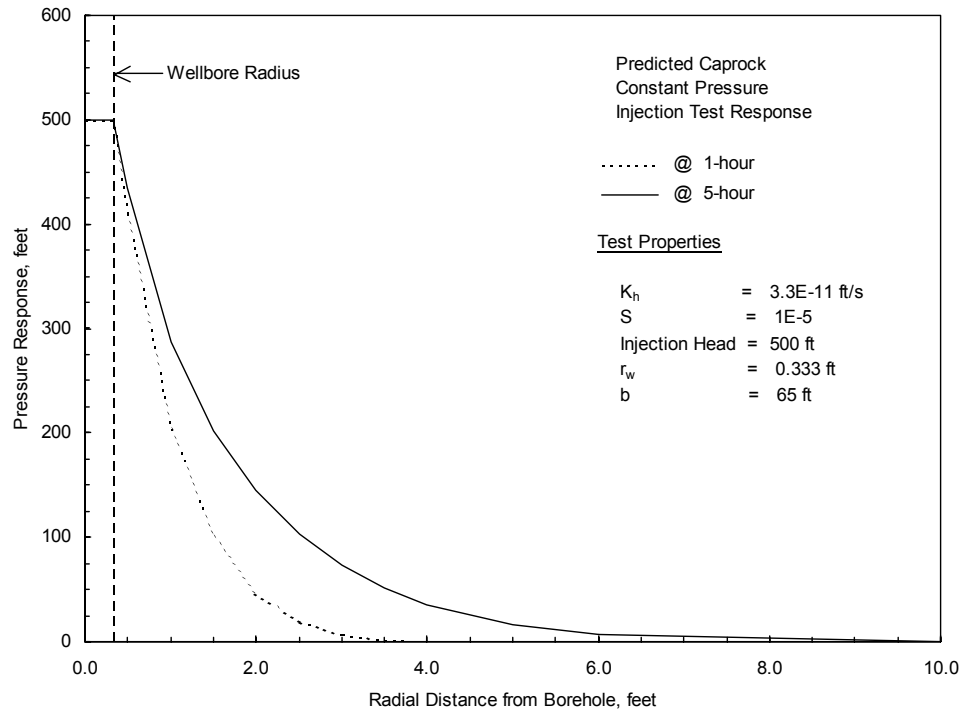


Figure E.7. Radius of Investigation for Constant Pressure Injection Test

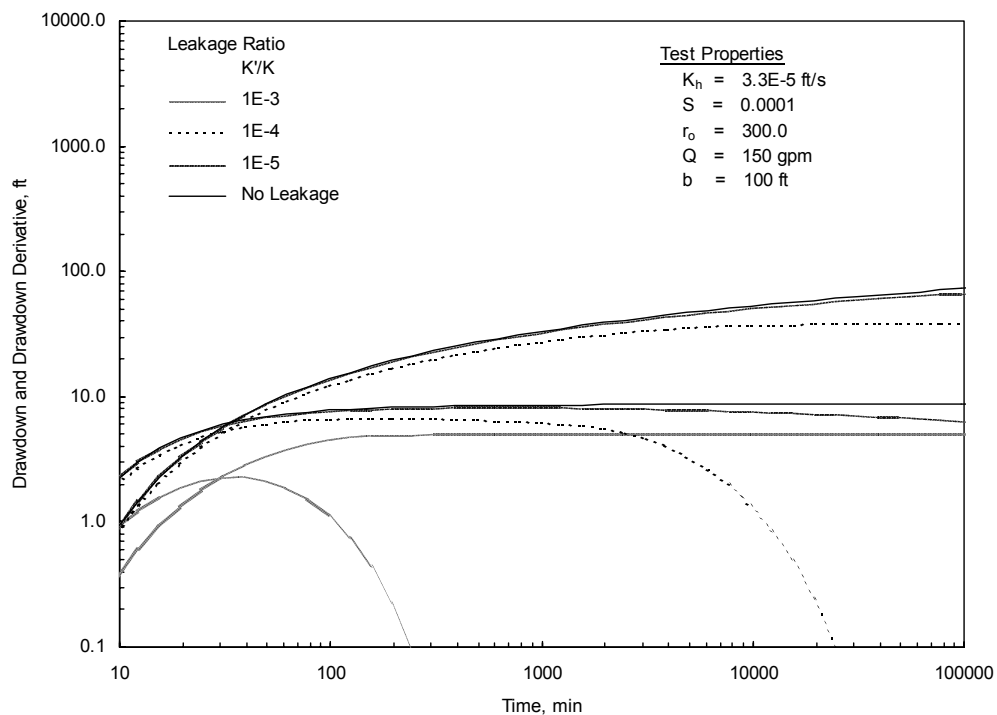


Figure E.8. Predicted Interflow Zone Drawdown and Drawdown Derivative Leakage Responses, During a Constant-Rate Pumping Test

caprock vertical permeability of $\geq 1.1 \times 10^{-9}$ m/s can only be resolved for tests conducted for durations of ~3 month or more. This relatively low sensitivity to leakage effects, and the test's inability to discern whether leakage is from the overlying caprock or underlying basalt flow interior, limits its use for quantitative caprock leakage assessment.

The above discussion pertains only to the observed response within the stressed (i.e., pumped) interflow zone. Information concerning caprock leakage can also be obtained by monitoring the response within the interflow zone immediately above the basalt caprock during testing. Figure E.9 shows predicted pressure responses near the top and bottom of a basalt caprock (flow interior) during testing for the same test conditions considered in Figure E.8 (for $K'/K = 1 \times 10^{-5}$). As indicated, a considerable length of time is required to propagate the test response across the caprock layer to the overlying interflow zone (~1 month). That overlying interflow zone permeability tends to dampen the propagated pressure response through the intervening caprock limits the practical use of this test for detecting test responses only for those associated with large caprock leakage.

E.3.5 Ratio Test Method

A multi-well test that was developed specifically for field assessment of caprock leakage characteristics (associated with natural gas storage applications) requires a constant-rate pumping test within the

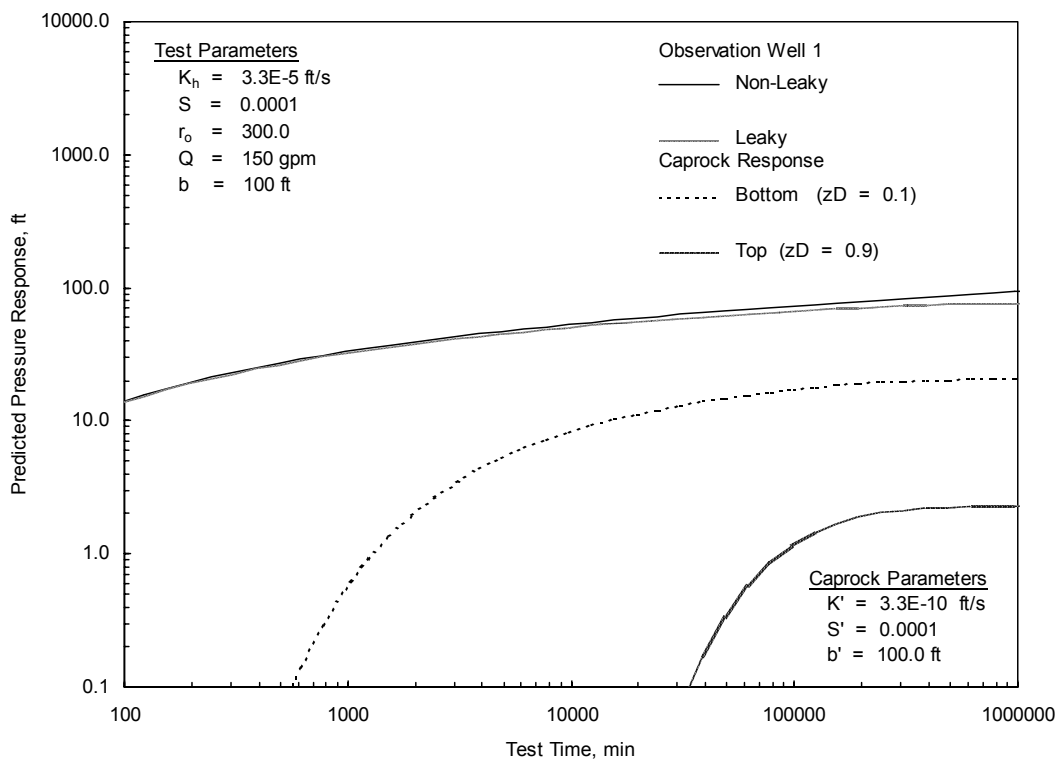


Figure E.9. Predicted Caprock Pressure Responses, During a Constant-Rate Pumping Test of the Underlying Interflow Zone

candidate storage horizon and monitoring of the associated pressure interference response in the adjacent low-permeability interval (e.g., Neuman and Witherspoon 1972). The “Ratio” of the drawdown response within the low-permeability caprock and the drawdown observed within the pumped interflow zone can be used to estimate the vertical hydraulic diffusivity (K_v/S_s') of the caprock horizon. When combined with independent estimates for S_s' (e.g., by direct field tests or laboratory core consolidation tests), the K_v for the caprock can be estimated.

These are two significant advantages of this method: it can be used to determine leakage and the K_v for caprocks at the point of measurement, and leakage responses can be observed more rapidly than discerned either within the pumped interflow zone or for waiting to propagating the stress response to adjacent interflow zones. For example, Figure E.9 indicates that a discernible response within the caprock (i.e., 10 ft into the caprock) would be observed in less than 1,000 min, for the specified test site conditions, which is significantly less than either the time needed for detecting a interflow leakage response (i.e., comparison of the non-leaky and leaky response curves) or the time required to propagate the pressure signal to the overlying interflow zone (i.e., the top caprock response). It should be noted, however, that only a few “Ratio” tests for confining layer/caprock characterization have been performed and published in the literature. “Ratio” test results for an interflow zone and its associated overlying flow interior caprock within the Grande Ronde Basalt are reported in Spane et al. (1983).

In summary, based on the available information, it is recommended that the quantification of intermediate- to large-scale caprock leakage characteristics be accomplished by the analysis of inter-well test responses between two or more well sites, at inter-well distances of ≤ 300 ft. For these distances, and the threshold caprock permeabilities expected, tests would likely have to be of long duration (i.e., ~1 to 3 weeks or more), and would be best quantified by monitoring both caprock and interflow zone responses. Because of the test observation requirements, the best opportunity for monitoring these responses is to use a dedicated multi-level monitoring system (e.g., Westbay Instruments, Mosdax system) within the observation and stress well locations.

E.4 Hydrology Test Equipment Considerations

Because of the depths (>460 m) and types of hydrologic tests recommended, downhole borehole test equipment systems commonly used in nuclear repository and petroleum industry are recommended for CRBG interflow zone characterization. As noted in Section E.1, these systems include an inflatable straddle-packer system for isolating selected interflow zones from the surrounding open borehole and a multiple-pressure sensor system for monitoring pressures within, below, and above the isolated interflow zone. Monitoring pressures above and below the inflow zone tested is required for assessing isolation during the period of testing. The pressures should be recorded at land surface on a “real-time” basis (e.g., wireline or telemetered system) for efficient control of tests and characterization costs. A shut-in tool immediately above the packer system also provides for test system isolation at test formation depths and facilitates performance of the hydrologic tests used during characterization activities.

E.4.1 Low-Permeability Test Systems

Although commercially available test systems are adequate for most interflow zone characterization investigations, hydraulic testing of low-permeability caprock intervals requires more sophisticated

equipment. As noted by previous investigators (e.g., Pickens et al. 1987), low-permeability formations can be significantly affected by borehole pressure history, temperature changes of fluid in the borehole, volume changes caused by deformation of test equipment, and the presence of gas in the formation and test system. Care, therefore, should be taken to minimize these extraneous effects during testing and to account for them in the test analysis. Extraneous effects that can adversely affect the performance and results of low permeability tests pertain mainly to test system deformation effects. Efforts, therefore, should be exercised to use test systems with minimal packer compliancy (i.e., elasticity) and shut-in tool displacement stresses (i.e., zero displacement shut-in tool). Because of the equipment constraints imposed by low-permeability testing, it is unlikely that one test system can be used universally for both interflow and caprock characterization applications.

E.4.2 Multi-Level Monitoring Systems

Commercially available straddle-packer test systems used for deep borehole testing can be configured to monitor the pressure response within a maximum of two isolated zones. The testing of individual basalt interflow zones within an open borehole section (testing strategy 2; Section E.1) requires the repeated moving of the straddle-packer system(s). Each resetting of the test packer system requires the equilibration/stabilization of test interval pressures prior to initiating hydrologic testing, which for low-permeability caprock testing can be quite lengthy. Significantly more information can be derived from use of a multi-level monitoring test system that would enable the simultaneous monitoring of hydrologic test responses within a number of permeable basalt interflows and overlying caprock layers with one test system packer installation. Specifically, the use of a multi-level monitoring system would allow:

- detailed hydrologic data coverage for more test zones than would be achievable using standard straddle-packer systems
- full borehole, inter-well characterization using one test system installation
- multiple-hydrologic characterization capabilities (e.g., multi-depth, caprock monitoring for leakage assessment, pressurized/formation depth hydrochemical sampling) not capable with standard-packer systems
- full cross-formational response assessment from the affects induced during drilling a neighboring borehole (i.e., before formal hydrologic testing).

Multi-level test systems have been used successfully for deep monitoring/characterization applications within various nuclear repository programs (e.g., Westbay Instruments, Inc.). They have also been used successfully to isolate and monitor selected CRBG interflow zones as part of the DOE programs. Other domestic program applications include Yucca Mountain (Nevada); Oak Ridge (Tennessee); and Los Alamos (New Mexico). International programs using multi-level monitoring systems to support site characterization applications include Nagra (Switzerland); Nirex (United Kingdom); Andra (France); ENRESA (Spain); JNC/JNFL (Japan); and KAERI (Korea). The number of intervals monitored using multi-level systems within nuclear repository programs generally range between 3 and 31 zones per installation. Figure E.10 shows a generalized example of a multi-level monitoring system deployment within a layered basalt flow sequence. In this example, basalt interflow zones (indicated by higher porosity zones in the figure) are isolated within the borehole by inflatable packers within adjacent basalt

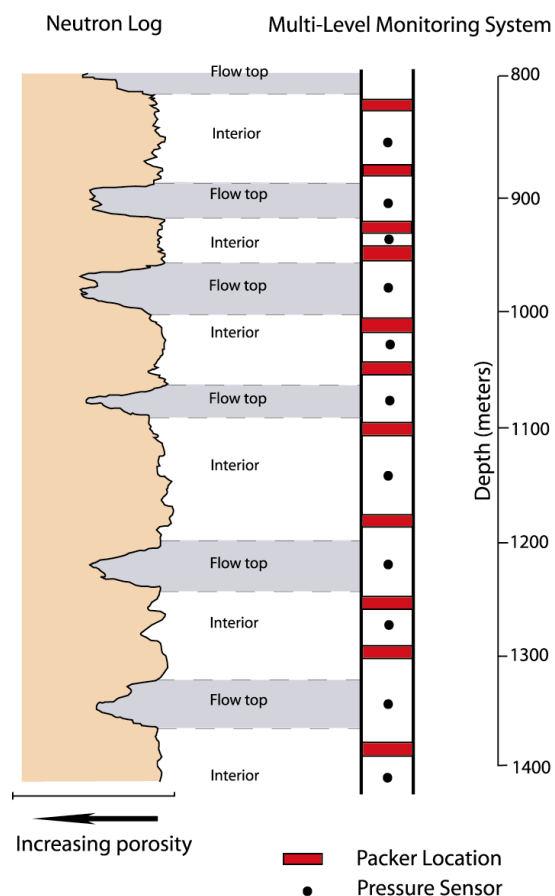


Figure E.10. Schematic of Generalized Multi-Level System for Pressure Testing in a Layered Basalt Flow Sequence

flow interior sections (indicated by low porosity sections in the figure). Pressure responses for controlled hydrologic tests are monitored for the various basalt interflow and interior zones using downhole pressure sensors that are situated between the isolating packers.

It can be assumed that the initial purchase/lease costs for multi-level monitoring systems are higher in comparison to standard straddle-packer systems. Offsetting these higher initial costs, however, are the cost savings associated with using a single borehole installation (versus repeated depth settings using conventional straddle packers) and the significant technical advantage of monitoring multiple test horizons during characterization activities. It should be noted, however, that while multi-level monitoring systems have demonstrated advanced deep borehole characterization/ monitoring capabilities (to depths of 4,000 ft), they have not been used in similar applications in the natural gas storage industry. This may be attributed to the gas industry's unfamiliarity with monitoring equipment developments within ground-water hydrology and nuclear repository studies. Nevertheless, multi-level monitoring systems offer distinct advantages not only in initial suitability assessment investigations, but also in any subsequent monitoring of the performance of a natural gas storage reservoir during use. This would be relevant not only for the ongoing evaluation for storage of natural gas within deep basalt formations, but also for all natural gas storage projects.

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Hydraulic Property Data from Selected Test Zones on the Hanford Site

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Note: This is a re-typed version of the original report. While the re-typed version has been reviewed for accuracy, errors may exist.

INTRODUCTION

Over the past eight years, hydrologists from the Basalt Waste Isolation Project (BWIP) have done extensive hydrologic testing in the Columbia River Basalts underlying the Hanford Site. The test intervals included within this report include all tested flow tops, interbedded sediments, flow interiors, and intraflow structures within the Saddle Mountains, Wanapum, and Grande Ronde Basalts. The majority of the tests consisted of single borehole tests conducted in boreholes that were progressively drilled and tested (Strait and others, 1982, RHO-BW-SA-189). Other tests were in existing boreholes in which test zones were isolated using straddle packers. Hydrologic tests conducted prior to 1982 used surface based depth-to-water measurements and tests conducted after 1982 utilized downhole pressure sensing probes for monitoring hydrologic test response.

DATA SOURCE

Sources of information contained within this document include BWIP documents (see references) and BWIP raw data files. All raw hydrologic data used to calculate the hydraulic properties are stored in the Hydrologic Testing Group field file and BWIP's Basalt Records Management Center (BRMC). Raw data is available upon request from the BRMC).

Basalt Records Management Center (no longer in existence)
Basalt Waste Isolation Project
Rockwell Hanford Operations
P.O. Box 800
Richland, Washington 99352
Telephone: (509) 376-1102

DATA LIMITATIONS

The hydrologic test data that have been verified by internal and/or external technical review and issued in a Rockwell Hanford Operations document (see references) has no limitations on its use. In this case the transmissivity values, in units of meters squared per second, have been determined to be accurate to two significant figures.

The values reported are considered to be the best estimate of transmissivity. The best estimate is obtained by examining the test results and associated analysis of the various hydrologic tests conducted (constant discharge, slug, pulse, constant drawdown, and constant head injection tests). Generally, results from long duration and/or high stress tests are given more weight in determining hydraulic properties, which are considered more representative of the test horizon.

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The effective test interval thickness is determined by examination of the geophysical logs and core, if available. The observed hydraulic head parameters, which were obtained from depth-to-water measurements, are recorded as elevation above mean sea level (MSL) to the nearest meter, with an assigned uncertainty (+) value. The uncertainty value results from non-equilibrium conditions at the time of measurement and instrument inaccuracies. The hydraulic head values have not been corrected for fluid-density effect, borehole deviation, and barometric or earth tide effects. Hydrologic test data that have not undergone verification by issuance of a document have not been validated by peer or technical review. In these cases, the transmissivities are presented in an order of magnitude range with hydraulic head values assigned a larger uncertainty value. Hydrologic test data over the past six years were collected in accordance to Basalt Operation procedure, C-2.8. Some of the existing data may have to undergo a qualifying process to meet the requirements of the 10 CRF 60, Subpart G Quality Assurance Program. This method has yet to be determined.

All raw data files and analyses of raw data were examined by BWIP hydrologists. Based on the examination, the use of the data was established. The “use code” developed was based upon results of the data review and is presented in Table 1. Data (e.g., transmissivity) contained within this report are preliminary and subject to change with further analysis. Changes to the data will be documented in subsequent revisions to this data package.

DATA DESCRIPTION

This data package contains the borehole, stratigraphic horizons, use code, isolated interval, effective test interval, transmissivity, observed hydraulic head, and the uncertainty in the hydraulic head.

Table 1. “Use Code” for Hydraulic Property Data

Use Code	Data Use
0	The data has been verified by internal and/or external peer or technical review and has unlimited use.
1	Hydrologic data and analyses appear to be of good quality, but the data has not been verified by any peer or technical review. The data use should be limited to conceptual modeling.
2	The data and analyses are of questionable quality and should not be used except in the most qualitative manner.

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APPENDIX A
Hydraulic Property Data

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
DC-3	Umtanum C/E	1	1092-1108	1092-1108	1.0E-12 to 1.0E-11	NA
DC-4	Rocky Coulee C/E	0	882-897	882-897	1.3E-12	NA
	Cohasset FT	1	899-915	904-909	1.0E-07 to 1.0E-06	SD-BWI-TI-175 128±?
DC-5	Cohasset FT	1	899-915	904-909	1.0E-07 to 1.0E-06	NA
	Cohasset C/E	1	964-976	964-976	1.0E-12 to 1.0E-11	NA
DC-6	Grande Ronde Composite	1	689-1321	NA	1.0E-05 to 1.0E-04	NA
	Grande Ronde FT	1	730-822	733-746 748-756 761-765 776-783	1.0E-05 to 1.0E-04	130±?
	Grande Ronde FT	1	822-882	821-851 853-872	1.0E-05 to 1.0E-04	130±?
	Umtanum FT	1	912-938	925-934	1.0E-07 to 1.0E-06	136±1.5
	Umtanum C/E	1	938-989	938-989	1.0E-12 to 1.0E-10	NA
	Umtanum FB	1	988-1076	933-1004 1015-1025 1030-1033	1.0E-06 to 1.0E-05	136±?
	Grande Ronde FT	1	1076-1166	1077-1082 1088-1092 1097-1098 1100-1102 1103-1113 1116-1120 1123-1159	1.0E-05 to 1.0E-04	137±?
	Grande Ronde C/E	1	1166-1271	1166-1271	1.0E-12 to 1.0E-11	NA
	Grande Ronde FT	1	1271-1321	1275-1286	1.0E-06 to 1.0E-05	140±1.5
DC-7	Grande Ronde Composite	1	1254-1526	NA	1.0E-06 to 1.0E-05	>122

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Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m ² /sec)	Observed Hydraulic Head (m) MSL
	Grande Ronde Composite	1	1256-1298	1261-1263 1279-1283 1287-1293	1.0E-09 to 1.0E-08	NA
	Grande Ronde 20 FT	1	1299-1351	1311-1317 1319-1344	1.0E-09 to 1.0E-08	NA
	Grande Ronde Composite	1	1355-1407	1367-1370 1374-1384 1386-1389 1392-1396	1.0E-07 to 1.0E-06	>124
	Grande Ronde 29 FT	1	1428-1471	1430-1433 1435-1466	1.0E-06 to 1.0E-05	123±.9
	Grande Ronde Composite	1	1472-1526	1482-1482 1487-1493 1495-1508	<1.0E-07 to	>119
DC-7/8	McCoy Canyon FT	1	1039-1060	1053-1059	1.0E-07 to 1.0E-06	124±1.2
DC-12	Rosalia FT	1	371-382	373-382	1.0E-04 to 1.0E-03	124±?
	Quincy IB/Roza FT	1	405-416	405-406 408-413 413-416	1.0E-04 to 1.0E-03	123±?
	Sentinel Gap FT	1	460-468	436-467	1.0E-05 to 1.0E-04	124±?
	Sand Hollow 2 FT	1	514-521	515-519	1.0E-05 to 1.0E-04	124±?
	Ginkgo 2 FT	1	582-605	584-585 586-605	1.0E-07 to 1.0E-06	124±?
	Ginkgo 1 FT	1	625-634	627-630 632-634	1.0E-04 to 1.0E-03	124±?
	Palouse Falls IB/Grande Ronde 1 FT	1	676-689	677-684	1.0E-07 to 1.0E-06	123±?
	Grande Ronde 2 FT	1	691-701	694-696 698-701	1.0E-06 to 1.0E-05	124±.6
	Rocky Coulee FT	1	734-746	736-743	1.0E-05 to 1.0E-04	124±.6
	Cohasset Composite	1	782-811	784-787 789-792 794-807	1.0E-07 to 1.0E-06	NA
	Grande Ronde 7 FT	1	859-867	862-865	1.0E-03 to 1.0E-02	124±.6

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Grande Ronde 8 FT	1	865-873	867-871	1.0E-04 to 1.0E-03	124±.6
	Grande Ronde Composite	1	908-961	913-927 942-947 949-955	1.0E-07 to 1.0E-06	NA
	McCoy Canyon FT	1	935-961	942-947 949-955	1.0E-08 to 1.0E-07	NA
	Umtanum FT	1	975-1000	979-988 990-995	1.0E-10 to 1.0E-08	NA
	Grande Ronde Composite	1	1018-1241	NA	1.0E-04 to 1.0E-03	124±?
	Grande Ronde Composite	1	1226-1241	1227-1237	1.0E-04 to 1.0E-03	124±?
	Grande Ronde Composite	1	1245-1358	NA	1.0E-04 to 1.0E-03	124±?
	Grande Ronde Composite	1	1324-1358	NA	1.0E-04 to 1.0E-03	124±?
DC-14	Elephant Mountain FT	1	112-145	120-126	1.0E-06 to 1.0E-05	115±?
	Rattlesnake Ridge IB	1	145-164	150-162	1.0E-05 to 1.0E-04	122±?
	Selah IB	1	206-234	214-231	1.0E-04 to 1.0E-03	124±?
	Asotin FT	1	268-276	270-276	1.0E-03 to 1.0E-02	150±?
	Asotin FT	1	277-281	279-281	1.0E-03 to 1.0E-02	150±?
	Asotin FT	1	282-295	288-294	1.0E-04 to 1.0E-03	NA
	Mabton IB	1	295-330	NA	1.0E-05 to 1.0E-04	149±?
	Priest Rapids FT	1	360-363	362-362	1.0E-04 to 1.0E-03	151±?
	Priest Rapids FT	1	365-371	366-370	1.0E-03 to 1.0E-02	150±?
	Priest Rapids FT	1	371-387	372-374	1.0E-03 to 1.0E-02	151±?
	Roza FT	1	392-409	395-408	1.0E-03 to 1.0E-02	150±?
	Frenchman Springs FT	1	451-462	455-459	1.0E-05 to 1.0E-04	148±?

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m ² /sec)	Observed Hydraulic Head (m) MSL
	Frenchman Springs FT	1	480-497	488-496	1.0E-04 to 1.0E-03	149 \pm ?
	Frenchman Springs FT	1	500-521	512-517	1.0E-04 to 1.0E-03	149 \pm ?
	Frenchman Springs FT	1	524-555	529-532 536-539	1.0E-04 to 1.0E-03	149 \pm ?
	Frenchman Springs FT	1	555-572	560-565	1.0E-04 to 1.0E-03	148 \pm ?
	Frenchman Springs FT	1	572-604	575-581 587-597	1.0E-03 to 1.0E-02	134 \pm ?
	Vantage IB/Grande Ronde FT	1	646-681	653-661 668-671 672-675	1.0E-04 to 1.0E-03	143 \pm ?
	Grande Ronde FT	1	718-733	722-729	1.0E-07 to 1.0E-06	133 \pm 1.5
	Grande Ronde FT	1	735-766	747-755	1.0E-06 to 1.0E-05	135 \pm .6
	Grande Ronde FT	1	810-876	819-824 833-840 861-871	1.0E-07 to 1.0E-06	133 \pm ?
	Grande Ronde FT	1	841-876	861-871	1.0E-09 to 1.0E-08	133 \pm 1.5
	Grande Ronde FT	1	878-907	882-900	1.0E-07 to 1.0E-06	133 \pm 1.5
	Umtanum FT	1	933-958	936-956	1.0E-05 to 1.0E-04	134 \pm .3
	Grande Ronde FT	1	969-983	975-980	1.0E-06 to 1.0E-05	134 \pm .3
	Grande Ronde FT	1	994-1017	999-1015	1.0E-05 to 1.0E-04	134 \pm ?
DC-15	Levey IB	1	84-105	87-95	1.0E-04 to 1.0E-03	112 \pm .3
	Rattlesnake Ridge IB	1	127-151	133-150	1.0E-04 to 1.0E-03	117 \pm .3
	Selah IB	1	183-192	183-188	1.0E-05 to 1.0E-04	109 \pm .6
	Esquatzel FT	1	192-201	193-198	1.0E-05 to 1.0E-04	109 \pm .6
	Cold Creek IB	0	217-240	220-239	3.1E-05	109 \pm .9
	Mabton IB	1	306-327	310-324	1.0E-05 to 1.0E-04	SD-BWI-TI-150 117 \pm .6

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m ² /sec)	Observed Hydraulic Head (m) MSL
	Priest Rapids	1	350-362	351-358	1.0E-07 to 1.0E-06	118±?
	Priest Rapids/Roza FT	1	372-394	378-392	1.0E-03 to 1.0E-02	118±.3
	Roza FT	1	414-424	416-419	1.0E-04 to 1.0E-03	118±.3
	Sentinel Gap FT	1	425-449	429-431	1.0E-06 to 1.0E-05	118±.6
	Wallula Gap FT	1	451-459	453-458	1.0E-03 to 1.0E-02	118±.3
	Sand Hollow 3 FT	1	459-473	463-468	1.0E-04 to 1.0E-03	118±.3
	Sand Hollow 2 FT	1	469-486	475-481	1.0E-03 to 1.0E-02	118±.3
	Ginkgo 2 FT	1	529-559	530-531 543-561	1.0E-06 to 1.0E-05	118±.6
	Ginkgo 1 FT	1	559-575	561-573	1.0E-03 to 1.0E-02	118±.3
	Vantage IB/Grande Ronde 1 FT	1	640-670	645-661	1.0E-06 to 1.0E-05	119±.6
	Rocky Coulee FT	1	679-714	685-686 690-699	1.0E-03 to 1.0E-02	118±.6
	Grande Ronde 5 FT	1	723-758	744-747	1.0E-06 to 1.0E-05	119±.6
	Cohasset FT	1	760-777	768-775	1.0E-04 to 1.0E-03	119±.6
	Grande Ronde 7 FT	2	808-823	810-812	<1.0E-04	119±?
	Grande Ronde 9 FT	1	821-842	832-834 840-842	1.0E-06 to 1.0E-05	119±.6
	Grande Ronde 11 FT	1	857-874	862-873	1.0E-06 to 1.0E-05	119±.6
	Umtanum FT	1	903-949	910-946	>1.0E-04	122±.3
	Grande Ronde 14 FT	1	989-1005	991-1003	1.0E-06 to 1.0E-05	112±?
	Very High Mg Flow FT	1	1006-1040	1016-1031	1.0E-06 to 1.0E-05	117±?
	Grande Ronde 17 FT	1	1101-1108	1102-1106	<1.0E-08	NA
	Grande Ronde 19 FT	1	1140-1172	1141-1168	1.0E-08 to 1.0E-07	NA

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Grande Ronde 20, 21 & 22 FTS	1	1261-1293	1267-1277 1281-1286	1.0E-06 to 1.0E-05	123±.6
DC-16A	Rattlesnake Ridge IB	1	204-255	208-246	1.0E-03 to 1.0E-02	137±?
	Selah IB	1	283-311	287-306	1.0E-05 to 1.0E-04	134±?
	Cold Creek IB	1	329-369	337-359	1.0E-06 to 1.0E-05	127±?
	Mabton IB	1	425-478	433-462	1.0E-04 to 1.0E-03	128±?
	Priest Rapids FT	1	515-527	520-521	1.0E-06 to 1.0E-05	116±?
	Roza FT	1	536-557	540-544	1.0E-02 to 1.0E-01	123±?
	Frenchman Springs FT	1	577-610	593-596	1.0E-03 to 1.0E-02	123±?
	Frenchman Springs FT	1	642-657	648-651	1.0E-05 to 1.0E-04	123±?
	Frenchman Springs FT	1	682-689	682-684	1.0E-03 to 1.0E-02	122±?
	Frenchman Springs FT	1	691-723	694-698 704-708 709-714 715-723	1.0E-05 to 1.0E-04	123±?
	Frenchman Springs FT	1	755-780	762-780	1.0E-03 to 1.0E-02	123±?
	Frenchman Springs F	1	788-802	792-802	1.0E-04 to 1.0E-03	123±?
	Vantage IB	1	814-832	825-828 828-828 829-829	1.0E-04 to 1.0E-03	123±?
	Grande Ronde FT	1	814-860	825-829	>1.0E-04	122±.6
	Grande Ronde FT	1	864-898	869-885	1.0E-07 to 1.0E-04	122±.6
	Cohasset FT	1	905-941	909-919 922-929	1.0E-08 to 1.0E-04	122±.9
	Cohasset C/E (vesicular zone)	0	941-992	941-992	2.6E-07	NA
	Cohasset C/E	1	961-992	961-992	1.0E-12 to 1.0E-11	NA
	Birkett FT	1	992-1024	1000-1019	1.0E-09 to 1.0E-08	122±.9

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Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Grande Ronde FT	1	1031-1065	NA	1.0E-10 to 1.0E-09	NA
	McCoy Canyon FT	1	1070-1082	NA	NA	123±?
	Umtanum FT	1	1104-1136	1105-1131	1.0E-06 to 1.0E-05	123±.9
	Umtanum C/E	1	1137-1178	1137-1178	1.0E-09 to 1.0E-08	NA
	Grande Ronde FT	1	1193-1231	1202-1209	1.0E-06 to 1.0E-06	123±.9
DC-19C	Priest Rapids FT	1	503-595	507-516	1.0E-04 to 1.0E-03	NA SD-BWI-TI-226
	Sentinel Gap FT	1	557-595	575-591	1.0E-05 to 1.0E-04	NA SD-BWI-TI-226
	Ginkgo FT	1	738-752	738-739 744-750	>1.1E-04	NA SD-BWI-TI-226
	Rocky Coulee FT	1	852-866	853-864	1.0E-07 to 1.1E-06	NA SD-BWI-TI-226
	Cohasset C/E	1	951-980	959-973	1.0E-11 to 1.1E-10	NA SD-BWI-TI-226
	Umtanum FT	1	1093-1118	1095-1116	1.0E-05 to 1.1E-04	NA SD-BWI-TI-226
DC-20C	Sentinel Gap FT	1	563-615	567-574	1.0E-03 to 1.1E-02	NA SD-BWI-TI-226
	Ginkgo FT	1	725-777	733-743	1.0E-05 to 1.1E-04	NA SD-BWI-TI-226
	Cohasset FT	1	892-944	894-897	1.0E-07 to 1.1E-06	NA SD-BWI-TI-226
	Umtanum FT	1	1080-1131	1083-1117	1.0E-07 to 1.1E-06	NA SD-BWI-TI-226
DC-22C	Rocky Coulee FT	1	877-922	878-886	1.0E-09 to 1.1E-05	NA SD-BWI-TI-226
	Umtanum FT	1	1126-1172	1127-1164	1.1E-05 to 1.1E-03	NA SD-BWI-TI-226
DC-23GR	Rosalia FT	1	410-434	NA	1.0E-03 to 1.0E-02	NA
	Sentinel Gap FT	1	481-498	NA	1.0E-02 to 1.0E-01	NA

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m ² /sec)	Observed Hydraulic Head (m) MSL
	Ginkgo FT	1	657-675	NA	1.0E-06 to 1.0E-04	NA
	Rocky Coulee FT	1	742-757	NA	1.0E-08 to 1.0E-07	NA
	Cohassett FT	1	797-821	NA	1.0E-09 to 1.0E-08	NA
	Birkett FT	1	891-907	NA	1.0E-08 to 1.0E-06	NA
	Umtanum FT	1	1006-1027	NA	1.0E-08 to 1.0E-05	NA
DB-1	Mabton IB	1	297-302	NA	1.0E-03 to 1.0E-02	117±?
	Priest Rapids FT	1	329-347	NA	1.0E-04 to 1.0E-03	NA
DB-2	Mabton IB	1	274-282	274-282	1.0E-03 to 1.0E-02	117±?
	Roza FT	1	355-363	356-360	1.0E-05 to 1.0E-04	NA
	Roza C/E	0	363-388	363-388	3.5E-10	NA
	Priest Rapids Composite	1	313-363	313-323 335-338	1.0E-04 to 1.0E-03	SD-BWI-TI-176 NA
DB-4	Mabton IB	1	415-428	415-428	1.0E-03 to 1.0E-02	128±?
DB-5	Mabton IB	1	248-277	254-277	1.0E-04 to 1.0E-03	124±?
DB-7	Mabton IB	1	182-247	237-247	1.0E-03 to 1.0E-02	122±?
DB-9	Mabton IB	1	141-180	149-180	1.0E-04 to 1.0E-03	123±?
DB-10	Mabton IB	1	242-272	257-272	1.0E-07 to 1.0E-06	125±?
DB-11	Mabton IB	1	216-316	264-307	1.0E-07 to 1.0E-06	206±?
	Priest Rapids FT	1	311-319	319-319	NA	288±?

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
DB-12	Priest Rapids FT	1	316-369	365-369	NA	292 \pm ?
	Mabton IB	1	115-156	115-156	1.0E-03 to 1.0E-02	122 \pm ?
	Priest Rapids FT	1	160-199	179-180	1.0E-02 to 1.0E-01	NA
	Priest Rapids FT	1	201-215	207-210	1.0E-02 to 1.0E-01	NA
DB-13	Elephant Mountain FT	0	115-116	NA	1.0E-03 to 1.0E-02	NA
	Rattlesnake Ridge IB	1	141-163	NA	1.0E-04 to 1.0E-03	NA
	Selah IB	1	219-225	NA	1.0E-04 to 1.0E-03	NA
	Cold Creek IB	1	264-287	NA	1.0E-04 to 1.0E-03	NA
	Mabton IB	1	364-394	364-394	1.0E-03 to 1.0E-02	129 \pm ?
DB-14	Rattlesnake Ridge IB	0	64-88	64-88	1.0E-05	136.5 \pm ? RHO-LD-67
	Selah IB	1	137-150	138-150	1.0E-05 to 1.0E-04	NA
	Cold Creek IB	1	188-202	188-202	1.0E-03 to 1.0E-02	NA
	Mabton IB	1	280-315	280-310	1.0E-04 to 1.0E-03	128 \pm ?
DB-15	Rattlesnake Ridge IB	0	46-68	51-68	5.1E-04 to	125 \pm ? SD-BWI-TI-130
	Selah IB	0	113-129	122-129	8.2E-06	124 \pm ? SD-BWI-TI-131
	Cold Creek IB	0	155-188	158-187	1.8E-03	124 \pm ? SD-BWI-TI-142
	Asotin/Umatilla FT	1	208-208	203-208	1.0E-04 to 1.0E-03	124 \pm ?
	Umatilla FT	1	207-230	210-230	1.0E-03 to 1.0E-02	124 \pm ?
	Mabton IB	1	230-257	230-257	1.0E-03 to 1.0E-02	124 \pm ?
	Priest Rapids FT	1	262-295	280-291	1.0E-03 to 1.0E-02	125 \pm ?

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REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Roza FT	1	319-337	323-337	1.0E-03 to 1.0E-02	125±?
	Roza C/E	1	338-350	338-350	1.0E-11 to 1.0E-10	NA
	Squaw Creek IB	1	377-393	383-393	NA	125±?
	Frenchman Springs FT	1	396-409	399-409	1.0E-04 to 1.0E-03	124±?
	Frenchman Springs FT	1	412-418	414-418	1.0E-04 to 1.0E-03	125±?
	Frenchman Springs FT	1	425-440	431-440	1.0E-04 to 1.0E-03	126±?
	Frenchman Springs FT	1	442-466	445-466	1.0E-05 to 1.0E-04	125±?
	Frenchman Springs FT	1	479-513	481-484	1.0E-04 to 1.0E-03	125±?
	Frenchman Springs FT	1	524-549	532-535	1.0E-08 to 1.0E-07	124±?
	Frenchman Springs FT	1	549-589	568-574	1.0E-09 to 1.0E-08	123±?
	Vantage IB	1	589-601	597-601	1.0E-12 to 1.0E-10	NA
RRL-2A	Mabton IB	1	416-471	426-442	1.0E-08 to 1.0E-07	127±?
	Priest Rapids FT	1	480-522	515-522	1.0E-04 to 1.0E-03	122±?
	Roza FT	1	529-540	533-536	1.0E-03 to 1.0E-02	123±?
	Upper Frenchman Springs FTS	1	581-677	586-593 641-644 676-677	1.0E-03 to 1.0E-02	123±?
	Lower Frenchman Springs FTS	1	684-806	692-699 725-735 759-763 796-800	1.0E-03 to 1.0E-02	122±?
	Vantage IB	1	812-827	814-820	1.0E-06 to 1.0E-05	122.6±?
	Grande Ronde FT	1	829-888	829-841 860-866	1.0E-06 to 1.0E-05	121±?
	Rocky Coulee C/E	1	894-909	894-909	1.0E-11 to 1.0E-10	NA
	Cohasset FT	0	909-920	912-918	4.5E-08	121.8±0.1

SD-BWI-TI-102

SD-BWI-DP-O51
REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m ² /sec)	Observed Hydraulic Head (m) MSL
	Cohasset C/E (vesticular zone)	0	932-967	940-945	2.8E-10	NA SD-BWI-TI-090
	Cohasset C/E	0	968-989	968-989	4.7E-12	NA SD-BWI-TI-109
	Birkett FT	0	990-1019	992-1016	8.2E-04	123.5±0.5 SD-BWI-TI-095
	Grande Ronde FT	1	1027-1055	1031-1035 1040-1047	1.0E-10 to 1.0E-09	NA
	McCoy Canyon FT	1	1056-1074	1059-1065	1.0E-10 to 1.0E-09	NA
	McCoy Canyon E	1	1088-1095	1088-1095	1.0E-11 to 1.0E-10	NA
	Umtanum Composite FTS	0	1088-1152	1096-1144	5.1E-04	123.7±0.1 SD-BWI-TI-105
	Umtanum FT	1	1135-1152	1140-1143	1.0E-06 to 1.0E-05	124±?
	Umtanum E	0	1147-1160	1147-1160	1.7E-11	NA SD-BWI-TI-107
	Umtanum E (fracture zone)	0	1152-1166	1164-1166	9.4E-04	NA SD-BWI-TI-089
	Umtanum FB	1	1170-1185	1170-1178	1.0E-04 to 1.0E-03	124±0.5
RRL-2B/A	Rocky Coulee FT	0	846-871	860-866	7.0E-06	NA SD-BWI-TI-329
RRL-2B/C	Rocky Coulee FT	0	846-871	858-864	1.6E-06	NA SD-BWI-TI-329
RRL-2C	Rocky Coulee C/E	1	882-889	882-889	1.0E-10 to 1.1E-09	NA SD-BWI-TI-329
	Cohasset FT	1	903-912	909-914	1.0E-10 to 1.1E-09	NA SD-BWI-TI-329
	Cohasset C	1	959-966	959-966	1.0E-10 to 1.1E-09	NA SD-BWI-TI-329
	Birkett FT	1	846-1038	985-997	1.0E-04 to 1.1E-03	NA SD-BWI-TI-329
	Birkett C/E	1	1010-1017	1010-1017	1.0E-10 to 1.1E-09	NA SD-BWI-TI-329
RRL-6	Frenchman Springs FB	1	641-653	647-651 654-655	1.0E-11 to 1.0E-10	NA

SD-BWI-DP-O51
REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Cohasset FT	1	940-951	943-948	1.0E-11 to 1.0E-10	NA
	Cohasset C/E	1	954-1016	954-1016	1.0E-14 to 1.0E-11	NA
	Birkett FT	1	1015-1041	1019-1039	1.0E-08 to 1.0E-07	NA
	McCoy Canyon C/E	1	1104-1126	1104-1126	1.0E-13 to 1.0E-10	NA
	Umtanum FT	1	1130-1165	1132-1161	1.0E-07 to 1.0E-06	NA
	Umtanum C/E	1	1166-1200	1166-1200	1.0E-12 to 1.0E-11	NA
	Grande Ronde 11 FT	1	1201-1231	1203-1206 1219-1221	1.0E-09 to 1.0E-08	NA
RRL-14	Cohasset FT	1	938-959	939-946 948-950	1.0E-06 to 1.0E-05	124±1.5
	Cohasset C/E	1	957-1010	957-1010	1.0E-12 to 1.0E-11	NA
	Birkett FT	1	1004-1037	1012-1036	1.0E-07 to 1.0E-04	125±1.5
	Umtanum FT	1	1132-1163	1135-1156	1.0E-06 to 1.0E-05	123±1.5
	Umtanum C/E	1	1164-1190	1164-1190	1.0E-13 to 1.0E-12	NA
	Very High Mg Flow FT	1	1181-1205	1194-1139	1.0E-08 to 1.0E-07	NA
McGee	Rosalia FT	1	247-251	NA	1.0E-02 to 1.0E-01	NA
	Upper Roza FT	1	282-285	NA	1.0E-02 to 1.0E-01	NA
	Lower Roza FT	1	313-334	326-333	>1.0E-03	279±?
	Sentinel Gap FT	1	335-356	339-350	>1.0E-03	277±?
	Sand Hollow 2 FT	1	402-420	406-418	>1.0E-03	278±?
	Sand Hollow 1 FT	1	428-439	429-433	>1.0E-03	278±?
	Silver Falls FT	1	440-452	443-450	>1.0E-03	278±?
	Ginkgo 2 FT	1	482-512	487-495	>1.0E-03	278±?
	Ginkgo 1 FT	1	510-533	517-524	>1.0E-03	279±?
	Frenchman Springs FTS	1	538-562	555-560	1.0E-06 to 1.0E-05	280±?
	Vantage IB	1	563-575	567-570	1.0E-08 to 1.0E-07	202±1.5

SD-BWI-DP-O51
REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
	Vantage IB	1	566-592	567-570 581-585	1.0E-07 to 1.0E-06	187±1.5
	Grande Ronde 2 FT		593-607	593-597	1.0E-04 to 1.0E-03	183±?
	Rocky Coulee FT	1	607-638	607-615	1.0E-04 to 1.0E-03	183±?
	Grande Ronde 4 FT	1	649-670	658-662	1.0E-07 to 1.0E-06	183±?
	Cohassett FT	1	667-712	670-676 679-681	1.0E-04 to 1.0E-03	183±?
	Grande Ronde 6 FT	1	729-769	739-747	1.0E-06 to 1.0E-05	180±1.5
	McCoy Canyon FT	1	799-841	799-802 805-813 815-819	1.0E-06 to 1.0E-05	183±?
	Very High Mg Flow FT	1	900-952	922-927 929-936 941-943	1.0E-07 to 1.0E-06	183±1.5
O BRIAN	Priest Rapids FT	1	183-213	209-212	1.0E-01 to 1.0E+00	NAA
FORD	Priest Rapids FT	1	218-237	226-229	1.0E-02 to 1.0E-01	NA
ENYEART	Priest Rapids FT	1	293-333	326-332	1.0E-02 to 1.0E-01	NA
699-52-48	Rattlesnake Ridge IB	0	44-59	44-59	1.0E-05	NA RHO-ST-38
699-53-50	Rattlesnake Ridge IB	0	45-59	45-59	1.0E-04	NA RHO-ST-38
699-51-46	Rattlesnake Ridge IB	0	37-50	37-50	1.0E-05	NA RHO-ST-38
699-52-46	Rattlesnake Ridge IB	0	50-69	50-69	1.0E-04	NA RHO-ST-38
699-50-45	Rattlesnake Ridge IB	0	41-54	41-54	1.0E-04	NA RHO-ST-38

SD-BWI-DP-O51
REV 2

Borehole	Strat. Horizon	Use Code	Isolated Interval (m)	Effective Test Interval (m)	Trans- missivity (m2/sec)	Observed Hydraulic Head (m) MSL
699-50-48	Rattlesnake Ridge IB	0	65-76	65-76	1.0E-04	NA RHO-ST-38
699-47-50	Rattlesnake Ridge IB	0	79-90	79-90	1.0E-04	NA RHO-ST-38
699-S11- E12A	Levey IB	0	69-86	73-81	1.0E-05	NA RHO-BWI-LD-27
69-114-60	Lower Saddle Mountains Composite	1	234-263	234-263	NA	149±?
BH-16	Selah IB	1	250-282	265-280	1.0E-05 to 1.0E-04	NA
BH-17	Asotin FT	1	312-334	314-318	1.0E-07 to 1.0E-06	NA
	Mabton IB	1	390-403	387-406	NA	125±?

Note: FT - Flow Top
 FB - Flow Bottom
 C/E - Colonnade / Entablature
 E - Entablature
 IB - Interbed

Composite - Test Interval spans more than one hydro-stratigraphic zone.